## Towards Embodied Evolution of Robot Organisms

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# 1

# Introduction

This thesis reports on years of exploration into a new research area: evolving robot organisms. The overarching long term vision is that of the Evolution of Things. The Evolution of Things is a concept for an evolutionary system where

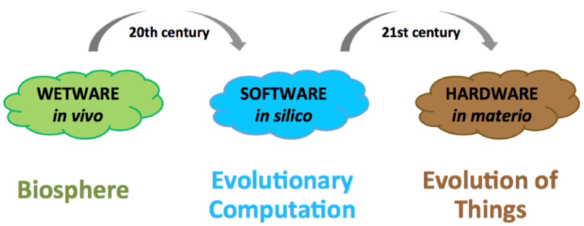



**Figure 1.1:** *The Evolution of Things positioned with respect to the underlying substrate*

the subject of evolution is physical artefacts. This presents the next step in the development of evolutionary systems as can be seen in Figure 1.1. In the 19th century evolution was used as a tool to explain a posteriori the emergence of life on earth. In the 20th century the rules of evolution were transferred to the computer to evolve digital entities like programs or solutions to numerical functions. Now we aim to take the next step, taking evolution back into the real world by evolving physical artefacts.

The artefacts evolved in the systems in this thesis are *robot organisms*. We distinguish two different ways of 'being an organism': transient and permanent. In the first case individual modules can assemble and disassemble themselves into 'multi-cellular' organisms, therefore being part of an organism is a transient state that the modules can enter and leave 'at will'. In the second case, being an organism is a permanent state. Such a robot organism is built from modules as well, but these modules do not need to be viable robots by themselves. In both cases we employ *online* evolution, which acts during the operational periods of the robot organisms, to adapt the bodies and the brains of these robot organisms. This is in contrast to *offline* evolutionary optimisation of these features which acts before the deployment.

The main research goal was to identify the principal challenges towards the Evolution of Things and to address some of these. In particular, the principal challenges for the Evolution of Things have been identified as: Birth, Lifetime Adaptation and Procreation. Birth is the process of building and delivering a new robot organism. Lifetime Adaptation is important because a new robot organism needs to learn to use its body after it has been delivered into the environment, both to survive in the environment as well as to be able to perform tasks. Procreation is an integral part of any evolutionary system, therefore to create a system in which robot organisms evolve they need to be able to reproduce.

We investigated these principal challenges for evolution of modular robot organisms in two different contexts. In the first context we investigated how transient 'multicellular' organisms emerge through evolution of the individual modules. In the second one, we investigated evolving robot organisms that form an artificial ecosystem where they can procreate and produce offspring. The research question in the second context was how such a system and could be constructed, and what the most important factors influencing the viability of such a system are.

This thesis covers a large range of research, the following are the main contributions.

1. We have identified the principal challenges for systems which implement Evolution of Things: Birth, Lifetime Adaptation and Procreation.

2. We show that it is possible to adapt the controllers of robot modules to adapt to the environment by aggregating into organisms.

3. We investigate lifetime adaptation methods for robot organisms. We show that RL Power is feasible as an online learning algorithm for gait learning of robot organisms.

4. We have created two prototype implementations of a robotic ecosystem. In both systems reproduction is de-centralised (e.g. mates are selected by the organisms, not by a central oracle).

   – One based on a de-centralised birth mechanism: fertilisation of eggs.

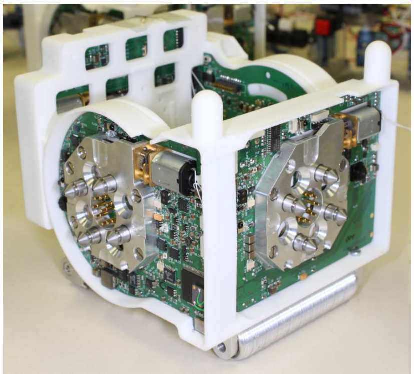
   – One based on a centralised birth mechanism: birth clinic.

5. We show that it is practicable to self-adapt the fitness evaluation time when evolving robot controllers online.

## 1.1 Methods

The methods in this thesis belong to the field of Evolutionary Robotics as described by Floreano, Husbands, and Nolfi [49]. As noted by Bongard [14] “the use of metaheuristics [i.e., evolution] sets this subfield of robotics apart from the mainstream of robotics research” which “aims to continuously generate better behavior for a given robot, while the long-term goal of Evolutionary Robotics is to create general, robot-generating algorithms”. Both the robots’ shapes,

**(a)** *The e-puck mobile robot: an example swarm robot [105]*



**(b)** *The KIT robot: an example modular robot*

**Figure 1.2**

also called *morphology*, and their minds, usually referred to as *controller*, can be the subject of evolution. In evolutionary robotics the robots are deemed autonomous entities for which the design of their bodies and minds develops in close interaction with the environment.

In addition to engineering new robots, evolutionary robotics is "useful both for investigating the design space of robotic applications and for testing scientific hypotheses of biological mechanisms and processes" as noted by [49]. Some examples where evolutionary robotics are used in such a manner are Waibel et al. [151]; Long [96], however this use is outside of the scope of this thesis.

Further to evolutionary mechanisms we use machine learning techniques to adapt the robots' controllers during their lifetime. In particular we use reinforcement learning to build optimal control policies.

For our experimental research we use different types of robotic hardware and simulation software. We base our work on two types of robotic hardware: *swarm robots* and *modular robots*. Swarm robots are typically small robots (most are between 2 cm and 30 cm in size) with wheels or tracks, a number of sensors (e.g. distance, light, etc.), and an onboard chip to run a controller (cf. Figure 1.2a).

With modular robots a robot consists of multiple autonomous robot modules. Robot modules are similar to swarm robots, they are similar in size and are also equipped with sensors and an on board computing chip. They differ in that they have the ability to connect to other robots of its kind through a connection mechanism (cf. Figure 1.2b). Thereby the robot modules have the ability to aggregate and collectively become a 'multicellular' modular robot. Notably, the modules typically have a servo motor allowing them to move a part of their body, this allows the aggregated robot to achieve locomotion.

Our work is carried out in simulation using two simulators: a low fidelity one called RoboRobo[1] developed by Bredeche et al. [20], and a high fidelity one called Webots[2] described by Michel [103]. The use of simulation for embodied evolution is paradoxical, however we feel it is warranted for two reasons. First, the current state of robotic hardware lacks the ability to provide a reproduction mechanism for robots. Second, using simulation allows us to quickly prototype our systems and thus prepare them for when such a reproduction mechanism does become available.

## 1.2 Overview of Papers in this Thesis

This section provides an overview of the papers this thesis is based on. The thesis follows the collection of papers approach, as such each paper is included as a chapter with only minor modification. This results in some overlap and repetition in some of the chapters, but also means each chapter can be read independently. There of course a narrative to the research in this thesis that is explained below.

The thesis is divided into three parts. Part I focusses on the emergence of organisms as an adaptation to the environment. Part II focusses on the construction of an ecosystem where organisms undergo online evolution. Part III investigates several aspects of online evolution that rose during my investigations. Note that the chapters in Part III investigate purely swarm systems and are

[1] RoboRobo: `https://github.com/ci-group/RoboRobo-Organisms`
[2] Webots: `http://www.cyberbotics.com`

therefore somewhat outside the main contributions of this thesis.

The chapters of Part I and II can be clustered around two ways of being an organism 'transient' and 'permanent'. The first option is tailored to be compatible with swarm operation of the modules. In this case the modules can operate as a swarm, e.g. each module can individually move, and when appropriate aggregate into an organism and operate as a collective. In the case of permanent organisms modules are assembled into organism in which they remain until the organism dies, at which point the modules are removed from the arena.

Below we position the research in this thesis is in light of the principal challenges that we identified. These challenges are: Birth, Lifetime Adaptation

**Birth** In the case of transient organisms birth is achieved by the individual modules aggregating into an organism. We have investigated two ways of achieving this aggregation: free-form and egg-based. The free from aggregation method is used in Part I, this form of aggregation allows the swarm to react to (changes in) the environment by forming organisms. Here the shape of the organisms is not encoded and therefore fully emergent.

In the case of the egg-based aggregation some modules in the swarm are designated to be eggs. These eggs are the starting points for new organisms and can be fertilised by passing organisms, in this manner the genome that encodes the shapes is transferred. The modules in the swarm that are not eggs can be recruited by an egg to form an organism, the genome encodes on which side the recruited module should connect. The advantage of using eggs in this manner is that it allows the organism to be built there where it is needed, near an obstacle for instance. This method is used in Chapter 9.

In the case of permanent organisms we chose to use a centralised method for birth in the form of a Birth Clinic. The reasoning behind this is both practical and ethical. Practically it is much easier to build, in real life and simulation, a single 'manufacturing plant' where organisms are constructed. Ethically it is a good idea to have a single point of failure for this system. This allows us to shut the system down by simply shutting down the birth clinic in case the system or evolution gets out of control. This method is used in Chapter 10.

**Lifetime Adaptation** The need for lifetime adaptation stems from the evolution of morphology. When a new organism is born it has inherited its morphology and its controller from its parents. The combination of the parent controllers is unlikely to fit the combination of the parent morphologies, therefore the child's controller needs to be adapted to fit its morphology. Learning algorithms for this are investigated in depth in Chapter 8.

Adaptation to the body is a necessity, on top we aim to have organisms adapt to certain tasks. In that case we need to combine the environmental pressure with tasks. This is the premise of the MONEE algorithm which is investigated in Chapters 15 and 16.

**Procreation** In Chapters 9 and 10 the shape and (part of) the controllers of the organisms are encoded in a genome. This genome is transmitted either by fertilising eggs or by mating with other organisms to create offspring. To create the offspring these genomes are recombined and mutated and then built, resulting in an evolutionary system.

Procreation in these chapters is proximity based, this means that an organism needs to move and be physically close to an egg or organism in order to transfer its genes. The consequences of such a method of procreation, e.g. a de-centralised one, are investigated in Chapters 9 and 10.

**Online Evolution** Finally in these systems we use online evolutionary algorithms to evolve robots, in contrast to traditional evolutionary robotics. Two aspects of online evolution warranted further investigations: 1) online evolutionary algorithms usually follow an island model architecture and 2) fitness evaluations in robots are, by necessity, conducted over a certain amount of time.

In Chapter 13 we investigate the influence of migration policies for an island model architecture in evolutionary robotics on the performance of the evolutionary algorithm. In Chapter 14 we investigate whether it is possible to self-adapt the fitness evaluation time.

## List of Papers

Below follows a list of the papers in this thesis and my contribution to their publication.

| Part | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|
| Emergence of Organisms | [1,2] | | | |
| Triangle of Life | | [3,6] | [4,7] | [5] |
| Aspects of Embodied Evolution | [8] | [9,10,11] | | |

[1] B. Weel, E. Haasdijk, and A. E. Eiben (2012). The emergence of multi-cellular robot organisms through on-line on-board evolution. In Di Chio et al, C. (Ed.) (2012). *Proceedings of EvoApplications 2012: Applications of Evolutionary Computation*, Number 7248 in Lecture Notes in Computer Science. pp. 124–134. Springer. **Winner of the Best Paper Award.**

This paper is the result of my master thesis. I designed the experiments, which I implemented in the RoboRobo simulator. The implementation here was quite substantial as the simulator had to be augmented with the ability for individual robots to connect to each other. I ran all the experiments, including the tuning of the algorithm and did the analysis of the results. Furthermore I wrote most of the paper including the related work, experimental setup, results and analysis and the conclusion.

[2] B. Weel, M. Hoogendoorn, and A. Eiben (2012). On-line evolution of controllers for aggregating swarm robots in changing environments. In C. A. C. Coello, V. Cutello, K. Deb, S. Forrest, G. Nicosia, and M. Pavone (Eds.), *Parallel Problem Solving from Nature - PPSN XII*, Volume 7491–7492 of Lecture Notes in Computer Science, pp. 245–254. Springer.

For this paper I designed the experiments, did the implementation and I ran all the experiments. Furthermore I did the analysis of the results and I wrote most of the paper; again writing the related work, experimental setup, results and analysis and conclusions.

[3] M. D'Angelo, B. Weel, and A. Eiben (2013). Online gait learning for modular robots with arbitrary shapes and sizes. In A.-H. Dediu, C. Martín-Vide, B. Truthe, and M. A. Vega-Rodríguez (Eds.), *Second International Conference on the Theory and Practice of Natural Computing (TPNC 2013)*, Number 8273 in LNCS, pp. 45–56. Springer.

I was the daily supervisor of our master student M. D'Angelo. I led the design of the experiments, set up of the experimentation environment and the analysis of the results. Furthermore for the paper I wrote large parts of the related work, results and analysis and conclusion sections.

[4] M. D'Angelo, B. Weel, and A. Eiben (2014). Hyperneat versus rl power for online gait learning in modular robots. In A. Esparcia-Alcázar (Ed.), *Proceedings of EvoApplications 2014: Applications of Evolutionary Computation*, Number 8602 in LNCS, pp. 777–788. Springer.

For this paper I led the design of the experiments and the analysis of the results. I wrote the majority of the related work, results and analysis and conclusion sections.

[5] B. Weel, M. D'Angelo, E. Haasdijk, and A. Eiben (2015). On-line gait learning for modular robots with arbitrary shapes and sizes. In *Artificial Life Journal*, under review

For this paper I reran a number of earlier experiments and implemented an extra learning algorithm with which I ran a control experiment. Furthermore I designed, implemented and ran a new investigation on a large number of random shapes. I did the analysis of the results and wrote almost all of the paper.

[6] B. Weel, E. Haasdijk, and A. Eiben (2013). Body building: Hatching robot organisms. In *Proceedings of the 2013 IEEE International Conference on Evolvable Systems (ICES)*, pp. 13–20. IEEE: IEEE Press.

For this paper I designed, implemented and ran the experiments. Furthermore I did the analysis of the results and wrote the large majority of the paper.

[7] B. Weel, E. Crosato, J. Heinerman, E. Haasdijk, and A. Eiben (2014). A robotic ecosystem with evolvable minds and bodies. In *Proceedings of the 2014 IEEE International Conference on Evolvable Systems (ICES)*, pp. 165–172. IEEE.

E. Crosato was a master student in our group for whom I was the daily supervisor. I led the design of the system and experimental setup. We implemented the system together. I led and performed large parts of the analysis and wrote the related work, results and analysis and conclusion.

[8] P. García-Sánchez, A. Eiben, E. Haasdijk, B. Weel, and J.-J. Merelo-Guervós (2012). Testing diversity-enhancing migration policies for hybrid on-line evolution of robot controllers. In Di Chio et al, C. (Ed.). *Proceedings of EvoApplications 2012: Applications of Evolutionary Computation*, Number 7248 in Lecture Notes in Computer Science. pp. 52–62. Springer.

P. García-Sánchez was a visiting PhD student in our lab. We jointly set up the simulation environment and did the programming. Secondly, I tuned the algorithm. Lastly I participated in the analysis of the results and writing the paper.

[9] C. M. Dinu, P. Dimitrov, B. Weel, and A. E. Eiben (2013). Self-adapting fitness evaluation times for on-line evolution of simulated robots. In C. Blum et al. (Eds.) (2013, 6-10 July). *Proceedings of the 15th Annual Conference on Genetic and Evolutionary Computation (GECCO '13)*, pp. 191–198. ACM.

For this paper I was the daily supervisor of C. Dinu and P. Dimitrov. I led the design of the experiments and implementation. I also led the analysis of the results and contributed to writing the paper.

[10] N. Noskov, E. Haasdijk, B. Weel, and A. Eiben (2013). MONEE: Using parental investment to combine open-ended and task-driven evolution. In A. Esparcia-Alcázar (Ed.), *Applications of Evolutionary Computation:*

*EvoApplications 2013*, Number 7835 in Lecture Notes in Computer Science, pp. 569–578. Springer-Verlag.

N. Noskov was a master student in our group for whom I was the co-supervisor. I led the set up the simulator the implementation of the experiments. Furthermore I contributed substantially to the design of the experiments, the analysis of the results and writing the paper.

[11] E. Haasdijk, B. Weel, and A. Eiben (2013, 6-10 July). Right on the MONEE. In Blum, C. et al. (Eds.) (2013, 6-10 July). *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO '13)*, pp. 207–214. ACM.

For this paper the same implementation was used as for [10]. Here I contributed to the design of the experiments, the analysis of the results and writing the paper.